Box Beam Stiffening Using Cold Formed Decks

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Conrad P. Heins[1], David Blank[2]

INTRODUCTION

During the last few years straight and curved box-beam bridges have become more predominant and have proved to be economical in terms of time required for construction and the amount of material required to support the design loads. However, one of the major problems in the box-beam design occurs during the intermediate stage of construction, and that is, after placing of the concrete and before the concrete has set. During this stage, the torsional resistance of the box-beams is limited to the steel section and is much smaller than that of the final structure. In many cases, this stage of construction may control the design of the bridge. If the box section could be stiffened, such that a pseudo closed section could be assumed, then the design stresses could be reduced.

The closing of a box-beam does occur through the use of cold formed decks, which are used in box girder bridges in order to save time and money in placing of the concrete slab. These forms at present, however are only used to support the slab until the concrete has hardened, and are not considered in developing any torsional resistance.

The purpose of this paper, therefore, is to detail the torsional interaction between the corrugated decking and a box girder, and present a design criteria. The results of study will involve both analytical and experimental investigations.

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THEORY

General

The torsional stiffness of open and closed cross sections can be calculated (4, 5) by the following equations;

$$K_T \text{ closed} = 4A_o^{\,2} \Big/ \oint_o^b (ds/t) \qquad (1)$$

$$K_T \text{ open} = \frac{1}{3} \sum_{i=1}^{n} b_i \, (t_i)^3 \qquad (2)$$

where:

A_o = the interior area of the section (cell)

t_i = thickness of section walls

b_i = length of walls

If a box section has a width and depth "d" and a constant thickness "t", the increase in stiffness of the closed vs. the open section, using Equations (1) and (2), is;

$$K_{Tc}/K_{To} = \frac{3}{4} \left({}^{d}/_{t}\right)^2 \qquad (3)$$

Considering a box-beam with d = 5.0' and t = 1/2", the ratio of K equals 10,800. Thus a closed box section affords 10,800. times more torsional rigidity than the open section. Therefore if a closed cross section can be accomplished by using the cold formed decking, the torsional stiffness of the box-beam can be substantially increased.

In order to accomplish this closure and to utilize the cold formed decking, the behavior of the deck must be studied. This decking by its "general" configuration, as shown in Figure 1 and 2, has orthotropic characteristics. The inclusion of an orthotropic deck if used in the computation of the torsional resistance of a box beam, would be too complex. Therefore, to simplify the procedure, an "equivalent thickness" criteria will be developed. This criteria assumes that the orthotropic cold formed decking can be replaced by an equivalent isotropic (imaginary) flat panel which in turn "closes" the box beam section, as shown in Figure 3.

The determination of this equivalent plate thickness was accomplished by using an energy method (1), in which the calculated strain energy stored in the cold formed decking was equated to the energy stored in a flat panel. This relationship then gives an equivalent plate thickness for a given panel configuration.

Cell Behavior

The general behavior of corrugated deck plates, subjected to shear, has been extensively investigated (1, 2, 3, 9). These panels have exhibited great capability to withstand greater shear loads without buckling, than plane plate shear panels. In particular, the predicted behavior of such panels, has been obtained by Horne (1). As mentioned previously, an energy technique was applied, to determine the deformation of a panel, when subjected to unit shear forces. This technique requires the cross sectional dimensions of the deck and span (2L). The resulting deformation equations have been incorporated into a computer program (15), in order to expidite the computations. The primary deformation of a single cell is shown in Figure 4, and is designated. $\Delta_1 \cdot F$ and the deformation of the entire panel is $\Delta_{11} \cdot F$; where Δ_1 and Δ_{11} are deformations per unit force, F = applied shear force. It is assumed in these computations that there is no slip between the deck and fasteners.

Uniform Plate Behavior

A uniform thick flat plate of dimension a x 2L, subjected to uniform shear, has a deformation according to the following (11);

$$\Delta_p = \gamma a \tag{4}$$

However, the shear $\tau = {}^{F}/(2L)t_e$, $\gamma = \tau/G$ and $G = E/2\ (1 + \mu)$, therefore Δ_p equals;

$$\Delta_p = \frac{2\ (1 + \mu)\ F.a}{(2L)\ t_e \cdot E} \tag{5}$$

where: E = modulus of elasticity
μ = poisson's ratio
a = cover width
2L = span length
F = applied shear force
t_e = equivalent plate thickness

Equivalent Plate Criteria

The deformation of a corrugation ($\Delta_{11} \cdot F$) as obtained using the energy method, and that of a uniform plate (Δ_p), as obtained from the same force F, can now be equated. This results in the following;

$$t_e = \frac{2(1 + \mu)\ a}{(2L) \cdot E \cdot \Delta_{11}} \tag{6}$$

which is the value of the equivalent plate thichness, which replaces the corrugated deck as shown in Figure 3.

Effects of Slip

The analytical determination of the deformation of a corrugated deck, assumes no slip between; (1) sheet - girder, (2) sheet - seam. It has however, been established from tests (2, 10, 3), that slip does occur and can alter the deformation pattern of the deck. In general the slip is a function of the geometry of the deck and the spacing and number of the fasteners (2), as given by the following;

1. Sheet - girder fastener slip

$$\Delta_{s_1} = 2\ \frac{a.P}{(2L)^2} \cdot F \cdot S \tag{7}$$

where: P = distance between fasteners
S = slip per unit load
a = total cover width
2L = span length
F = shear force

2. Sheet-Seam Fastener Slip

$$\Delta_{S2} = \frac{(N_{Sh} - 1)}{N_S} \cdot F \cdot S \tag{8}$$

where: N_{Sh} = number of sheets

N_S = number of seam fasteners in each side-lap

S = Slip per unit load

F = Shear Force

The value of the slip coefficient S as given in Reference (2), is obtained from the following approximate equation;

$$S = .045 \left(\frac{.028}{t} \right) \tag{9}$$

where t = thickness of the corrugation.

The effect of slip can now be incorporated into the equivalent plate thickness equation (6), by adding to cell distortions Δ_{11}, the slip distortions Δ_{S1} and Δ_{S2}. The value of Δ_{11}, however is a known quantity and provides a thickness te. Thus, by equating Equations (7) and (8), to Equation (5), a modification to the t_e value which includes slip, is obtained directly and is;

$$t_{em} = \frac{2(1+\mu)a}{(2L)\cdot E} \quad \frac{1}{\left[\frac{2(1+\mu)a}{(2L)E\,t_e} + \frac{2aP}{(2L)2}\cdot S + \frac{(N_{sh}-1)}{N_S}\cdot S\right]} \tag{10}$$

where: t_{em} = modified equivalent plate thickness to account for slip

t_e = equivalent plate thickness due to cellular distortions, Equation (6).

EQUIVALENT PLATE THICKNESS TABLES

A computer program (15), which computes directly the equivalent plate thickness per Equation (6), has been used to develop tables of decks which are manufactured by three companies (12, 13, 14). The configuration of these decks is shown in Figure 5, and the resulting t_e(TE), is given in Table 1, for one deck type (12). Tabular values for the other type decks (13, 14), yield similar results. It should be noted, that these equivalent plate thicknesses do not include the effect of slip. If slip is to be considered, Equation (10), should be used in conjunction with the tabular (t_e) values.

BOX BEAM DATA

In order to illustrate the advantage of closing a box bridge beam, by use of the cold formed deck, a study (15) was first conducted on the evaluation of the properties of typical box beams (7), shown in Figure 6 and Table 2. The torsional properties of the box section, without the forming or concrete deck, were first computed, using a numerical procedure (4, 8, 11). The top of the box section was then closed by an equivalent plate (t_{em}) which varied between .0001 and .04 inches, and the properties then computed.

The closing of the box beam should increase the torsional stiffness and thus reduce the warping stresses. In general this reduction can be written as;

$$\bar{\psi} = \frac{(\phi'' W_n) \text{ closed}}{(\varphi'' W_n) \text{ open}} = \frac{\sigma_{w_c}}{\sigma_{w_o}} \tag{11}$$

where: ϕ'' = the second derivative of the rotation of the beam

W_n = warping statical moment of the beam

σ_w = warping stress

The rotation ϕ and its derivatives as a function of the torsional cross sectional properties (4, 5, 6), span length of the beam and boundary conditions.

Considering a pinned-pinned beam in torsion, subjected to a uniform torque M, the maximum ϕ'' function can be readily evaluated (6, 15). Evaluation of and Wn, for the open and closed box beams given in Table 2, has resulted in the determination of the ratio $\bar{\psi}$ vs. t_{em}, as shown in Figure 7. This figure thus permits the determination of the reduction of warping stress of a open cross section when closed by a top plate of thickness t_{em}. The maximum stress is on the top flange, point 2, as shown in Figure 6.

EXPERIMENTAL STUDIES

Two types of experimental tests were conducted, in order to determine the valadity of the equivalent plate criteria. The first experiments were in plane load diaphragm tests, similar to those conducted by previous investigators (2, 9). The test frame consisted of two parallel W12 x 27 steel sections and four 3 x 2 x 1/8 angles. Two angles were welded to the top flange of the W shapes and two spanned perpendicular between the W shapes. The corrugation was then attached to this frame by self tapping screws with the corrugation cells parallel to the W shape. The in plane load was applied to one of the W shapes, with the other shape fixed to the floor. In plane deformations, along the edge of the corrugation were recorded for each load increment.

Six diaphragm tests were conducted, whose characteristics are described in Table 3 . The resulting equivalent plate thickness using the experimental data and theory, is given in Table 4 . It should be noted that the theoretical slip between the angle which is perpendicular to the load beam, must also be included in the theory. This relationship, as given in Reference (2), is

$\Delta S_3 = 2 \frac{S}{Nr} \cdot F$, where Nr = number of fasteners between the sheet and angle.

The second type of tests that were conducted, consisted of the torsional response of a box beam. The box section consisted of two C 12 x 20.7 channel beams, which act as a web of the box and top and bottom corrugated deck panels which act as flanges of the box. The box beam has one end (loaded portion) which is free to rotate and one end restrained, as shown in Figures 8 and 9.

The torsional load was applied by means of two calibrated jacks. The rotation of the beam was measured along the length, by means of dial and rotation gages, as shown in Figure 8 .

Four different box beams were tested. Each box had essentially the same dimensions, except the flange elements consisted of various deck configurations, as given in Table 5 . The equivalent plate thickness t_e and the modified plate thickness t_{em}, using Equations (6) and (10), have been computed and are also listed in Table 5 .

The results of the box beam tests, were used to determine the torsional ridity GK_T. The experimentally determined GK_T could then be compared to the theoretical values, using Equation (1) and the equivalent plate thickness t_e or t_{em}.

The resulting torque (T) vs. rotation ϕ, at various cross sectional locations were determined. This information was then translated into torque (T) vs. ϕ' (change in rotation per unit length). Then from the basic equation;

$$T = GK_T \phi' \tag{12a}$$

or

$$GK_T = T/\phi' \tag{12b}$$

which represents the slope of the T vs ϕ' curve. A plot of the T vs. ϕ and T vs. ϕ' , for the test B4, is shown in Figure 10 and 11. Similar curves have been plotted for the other tests, and are listed in Reference (15).

The resulting stiffnesses GK_T, computed from theory and equivalent plate thicknesses and the experimentally determined values, are given in Table 6 . The results indicate reasonable corrulation and the importance of the slip. Also the criteria of using an equivalent plate thickness, is feasable.

APPLICATION

In order to illustrate the use of the decking, in reducing the effective warping stress of a box beam, a two lane - two girder box beam 100' long will be analyized. The details of this box are given in Table 2. The loads that will be applied to this box are a uniform vertical load $W = 2.2^K/ft$ and a uniform torque $M = 37.4$ K-in/ft. These loads are due to the weight of the 8" concrete slab, parapit, curbing and deck form (15). The beam is assumed simply supported in bending and torsion.

1. Bridge Form

The estimated uniform weight to be supported by the forming is 153 psf, on a span of 6'-8". Examination of various load tables (12, 13, 14), indicates that a form with 6" pitch - 19 gage can support this load.

2. Equivalent Plate Thickness t_e

With the form selected, the t_e value can be obtained by use of Table 1. For a 6" pitch, 19 gages, 7' long form, the t_e = .011 inches.

3. Modified Plate Thickness t_{em}

The effect of slip can be included by using Equation (10). The parameters for this equation, relative to this analysis, are as follows;

$t = 0.0413$ (19 gage), $\mu = .30$, $a = 1200$ in. (Box Length)

$E = 30 \times 10^3$ Ksi, $(2L) = 80$ in. (Form Length)

$P = 6$ in. (distance between fasteners - pitch of form)

$S = .045 \left(\frac{.028}{t}\right) = .03$

N_{sh} = No. of sheets = $\frac{a}{\text{cover width}} = \frac{1200.}{24} = 50.$ (Reference 12)

N_S = No. Seam Fasteners = 5

$$t_{em} = \frac{2(1+\mu)a}{(2L)E} \quad \frac{1}{\left[\frac{2(1+\mu)a}{(2L)E\ t_e} + \frac{2aP}{(2L)}\ S + \frac{(N_{sh}-1)}{N_S}.\ S\right]}$$

$$t_{em} = \frac{(2.6)(1200.)}{(80)\ (3 \times 10^4)} \quad \frac{1}{\left[\frac{(2.6)\ (1200.)}{(80)\ (3 \times 10^4)\ (.011)} + \frac{(2400.)\ (6)}{(80)^2}(.03) + \frac{49}{5}(.03)\right]}$$

$$t_{em} = 1.3 \times 10^{-3} \left[\frac{1}{.118 + .0675 + .294}\right]$$

$$t_{em} = \frac{1.3 \times 10^{-3}}{.4795} = .00272 \text{ inches}$$

4. Normal Bending Stress

The bending cross section property of the box beam is;

$$I_x = 52{,}230.0 \text{ in}^4$$

$$C_T = 31.7 \text{ in}$$

The maximum bending moment is $M = \frac{WL^2}{8} = 33{,}000.$ k-in, therefor the maximum bending stress on the top flange (Pt.2), is;

$$\sigma = \frac{MC}{I} = \frac{33{,}000}{1650.} = 20.\text{ksi}$$

5. Warping Torsional Stress

(a) Open Section

The torsional properties of the open box section are;

$$K_T = 26.92 \text{ in}^4,\ I_w = 9683. \times 10^4 \text{ in}^4,\ W_{n_2} = 1656.7 \text{ in}^2$$

as given in Reference (15). The constant $a = \sqrt{EIw/GK_T}$, is then equal to $a = 3060.$in, as required by the torsional analysis criteria Reference (6).

The function L/a = 1200/3060 = .392, and therefor $\phi'' \frac{GK_T}{M} = .02$ or $\phi'' = .02 \frac{M}{GK_T}$

The warping stress in therefor;

$$\sigma_{w_o} = EW_n \phi'' \quad \text{or}$$

$$\sigma_{w_o} = EW_n (.02) \frac{M}{GK_T}$$

$$\sigma_{w_o} = \frac{30 \times 10^3}{11.2 \times 10^3} \times \frac{1656.7}{26.92} \times \frac{(37.4)}{12} \times (.02)$$

$$\sigma_{w_o} = 2.68 \times 61.4 \times 3.11 \times .02$$

$$\sigma_{w_o} = 10.2 \text{ ksi}$$

b. Closed Section

Equation (11), relates the reduction in stress in the open section, when the section is closed by a plate. Therefor;

$$\sigma_{w_c} = \bar{\psi} \times \sigma_{w_o}$$

The reduction factor $\bar{\psi}$ is found from Figure 7, for L = 100, B = 96in. and t_{em} = .0072in, or

$$\bar{\psi} = .35$$

Therefor

$$\sigma_{w_c} = .35 \times 10.2$$

$$\sigma_{w_c} = 3.60 \text{ ksi}$$

6. Total Stress

The total induced maximum normal stress for the open and closed sections are given in Table 7. As can be seen the closing of the cross section, reduces the warping stress by 70% and thus a lower total stress.

RESULTS AND CONCLUSIONS

An analytical method is presented by which the effect of corrugated bridge forms can be utilized in increasing the torsional resistance of bridge box beams. Tables are presented which permit rapid determination of equivalent plate thicknesses for particular bridge forms. A complete set of tables are available elsewhere (15).

A series of box beam tests were also conducted, in order to determine torsional rigiditiy of the boxes composed of deck elements, and to compare these results with the theory. The results indicate reasonable corrulation and indicate the importance of the fasteners in controlling slip.

In general the results of this study indicate the feasability of using corrugated deck to stiffen box beams. Studies to investigate the minimization of slip, through better fasteners or modification of the deck should prove usefull.

ACKNOWLEDGEMENTS

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NOTATIONS

a	=	torsion constant equal to $\sqrt{EIw/GK_T}$
a	=	corrugation panel width
A_o	=	enclosed area of hollow cross section
b	=	length of thin walled element
c	=	distance from neutral axis of beam to top flange
d	=	depth of corrugation
E	=	Modulus of elasticity
F	=	diaphragm force
G	=	$(E/2(1+\mu))$ = Shear modulus
I_x	=	Bending moment of inertia
I_w	=	warping constant
K_T	=	torsional constant
(2L)	=	length of corrugated deck
N_r	=	number of sheet-rafter fasteners
N_s	=	number of seam fasteners
N_{sh}	=	number of sheets (beam length $\div$ sheet width)
P	=	pitch
S	=	slip between corrugation and support
T	=	torque
t_e	=	equivalent plate thickness (no slip)
t_{em}	=	modified equivalent plate thickness - (include slip)
Z	=	fraction of span length
ϕ	=	angle of rotation

ϕ' = rate of change in ϕ

μ = Poisson's Ratio

Δ = lateral displacement

σ = normal stress

ψ = reduction factor

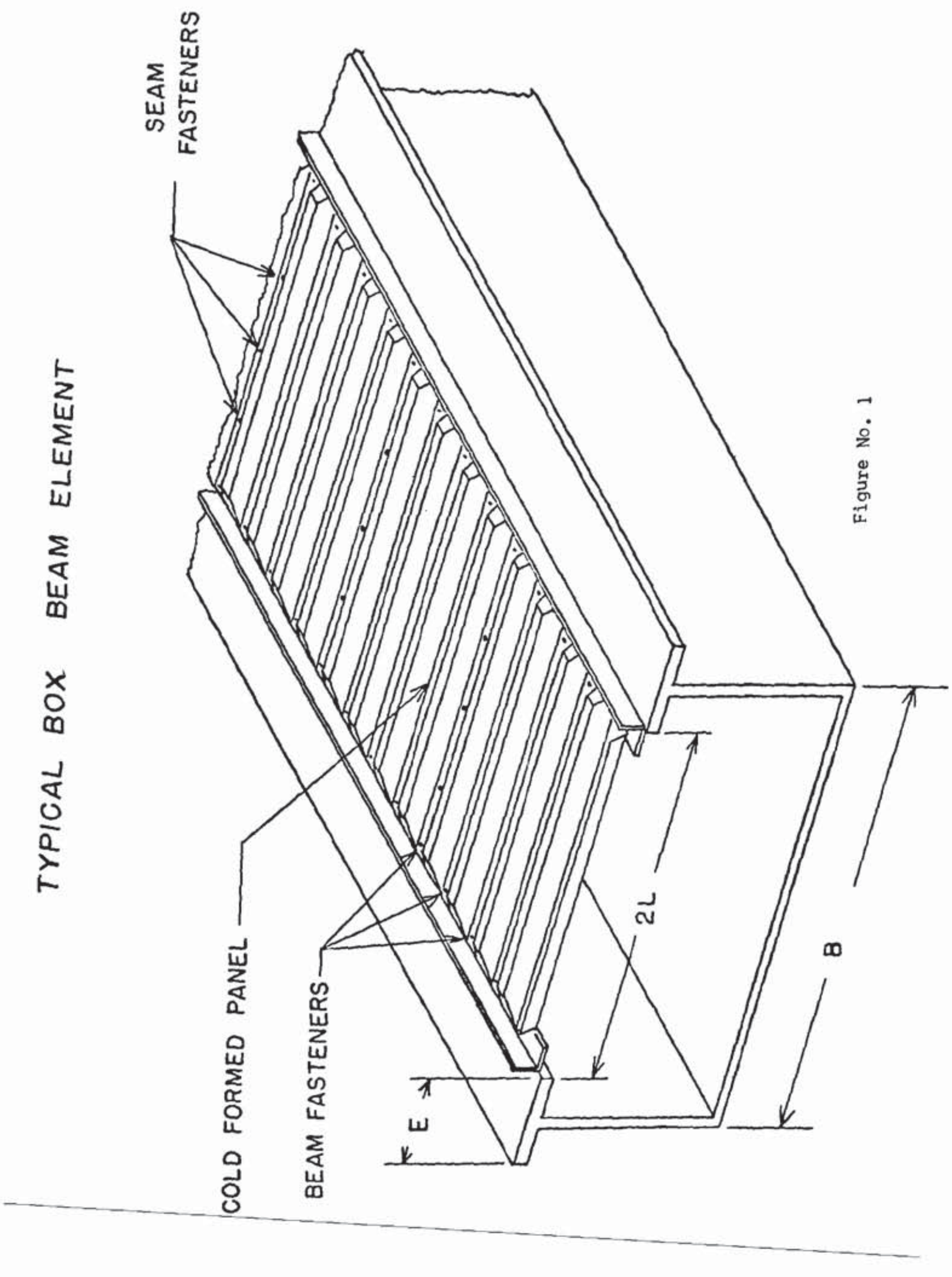
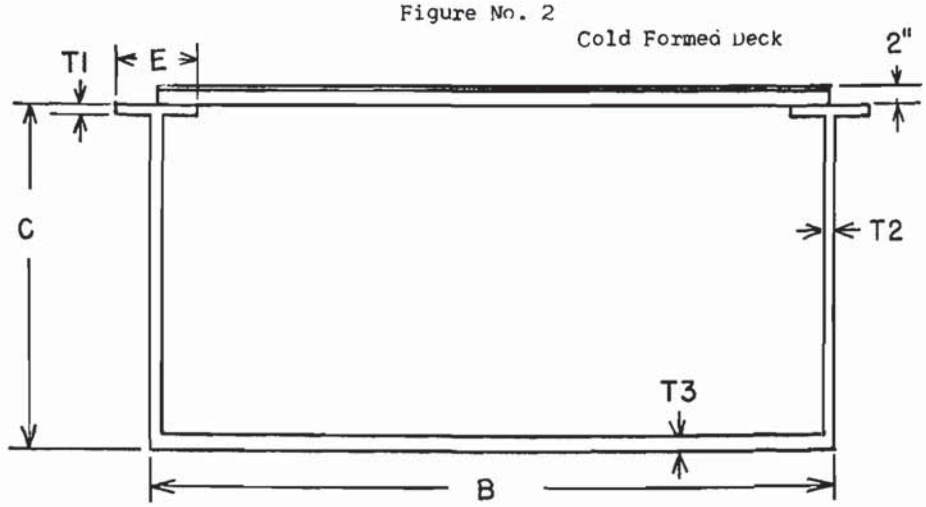

TYPICAL BOX BEAM ELEMENT
SEAM FASTENERS
COLD FORMED PANEL
BEAM FASTENERS
E
2L
B

Figure No. 1

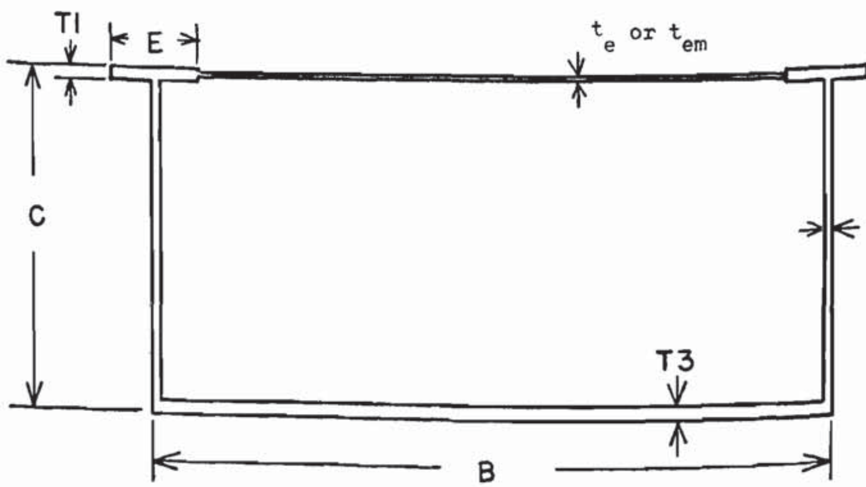
BOX BEAM: TYPICAL DIMENSION

Figure No. 2



BOX BEAM: EQUIVALENT THICKNESS CRITERIA

Figure No. 3



DEFLECTION CONFIGURATION OF CORRUGATION

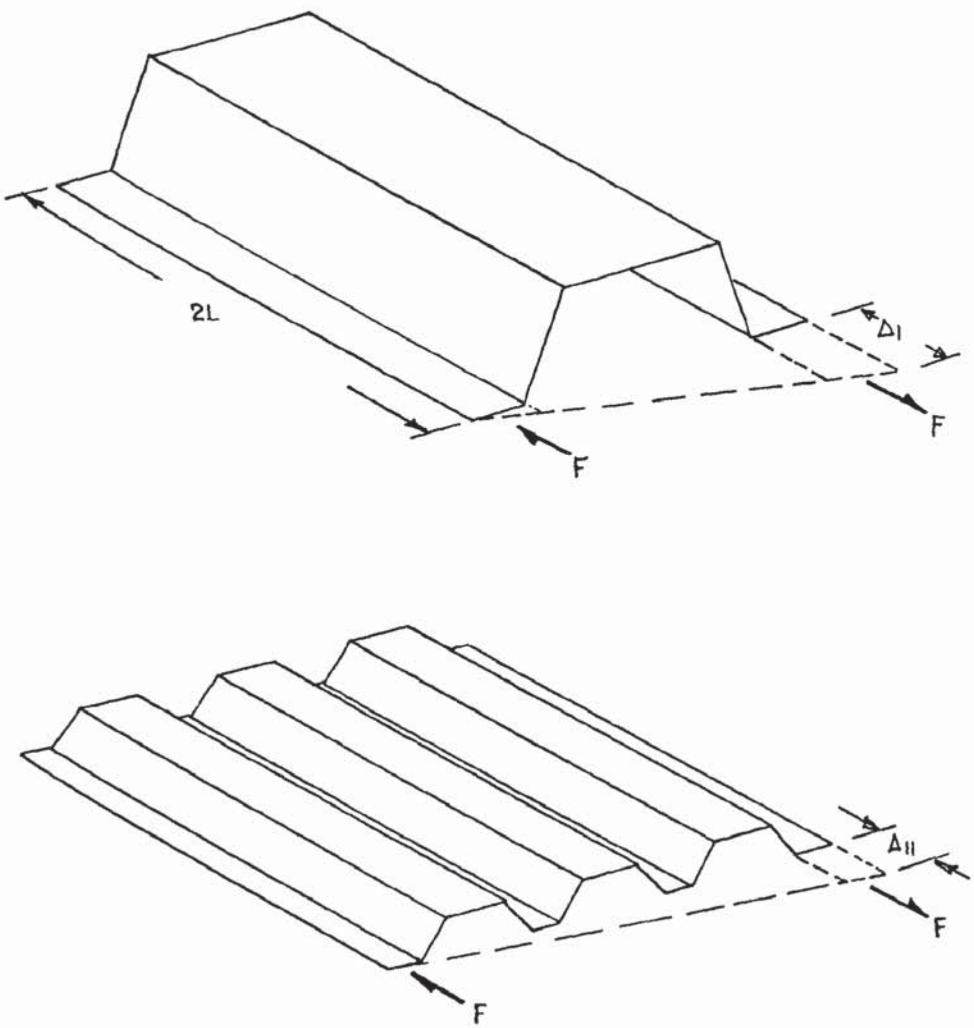


Figure No. 4

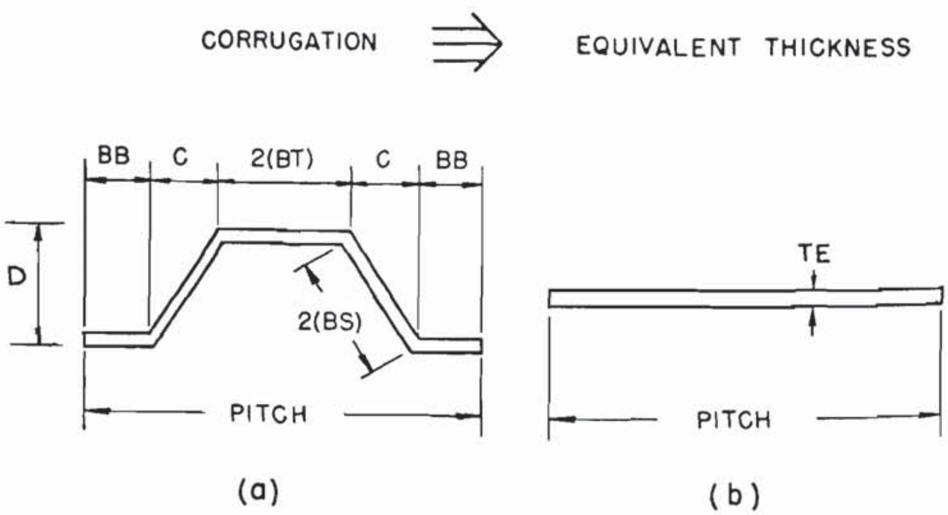
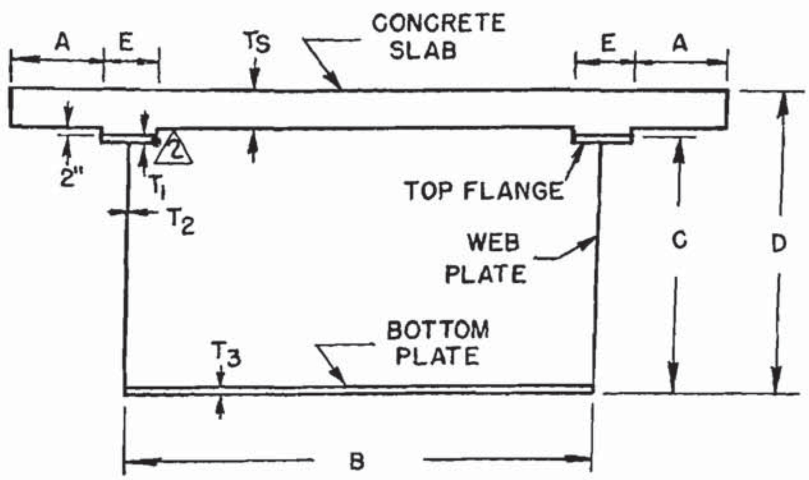

CORRUGATION
EQUIVALENT THICKNESS
BB
C
2(BT)
C
BB
D
2(BS)
PITCH
TE
PITCH
(a)
(b)

Figure No. 5



(A) INTERIOR BOX SECTION

Figure No. 6

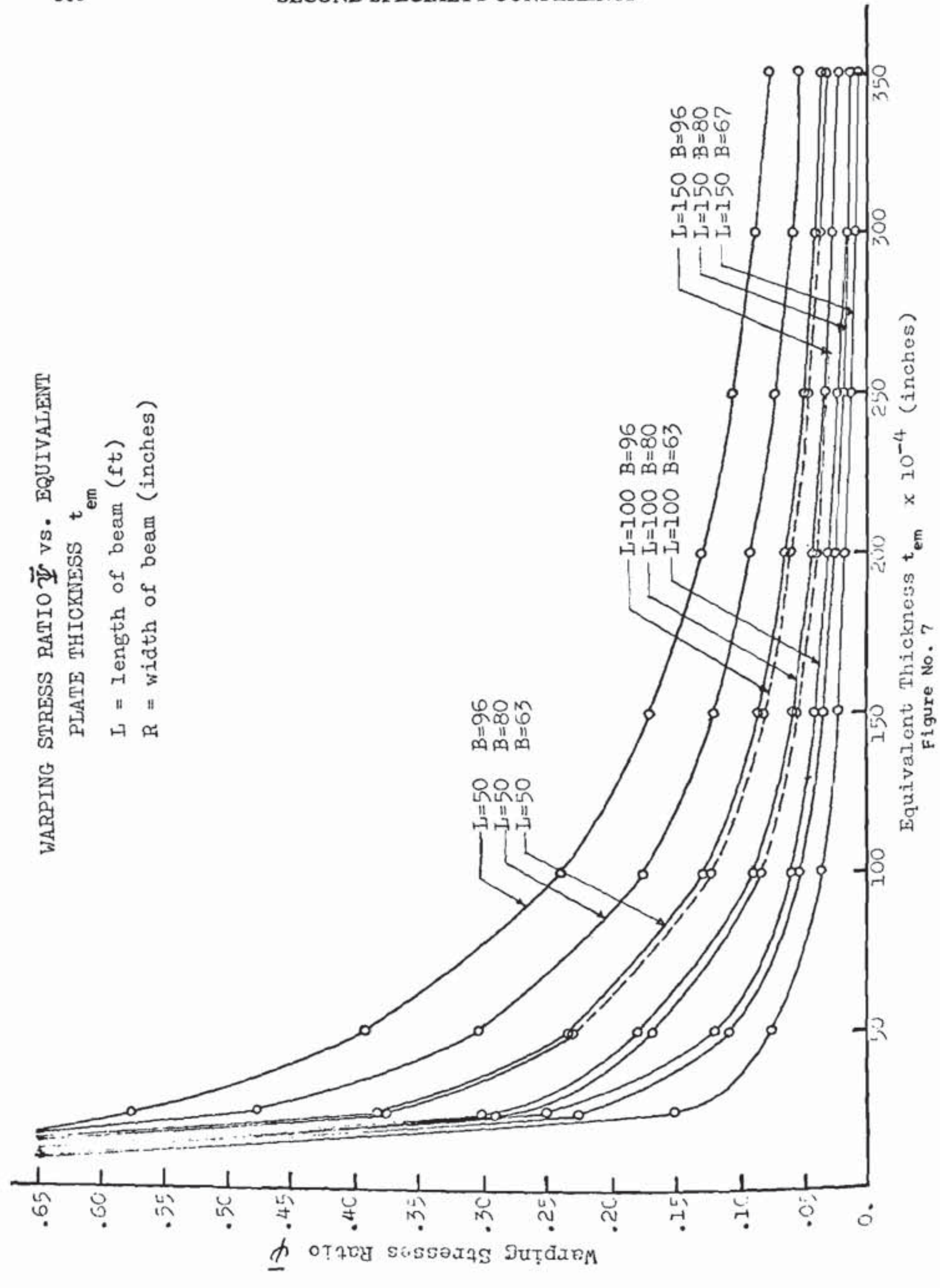
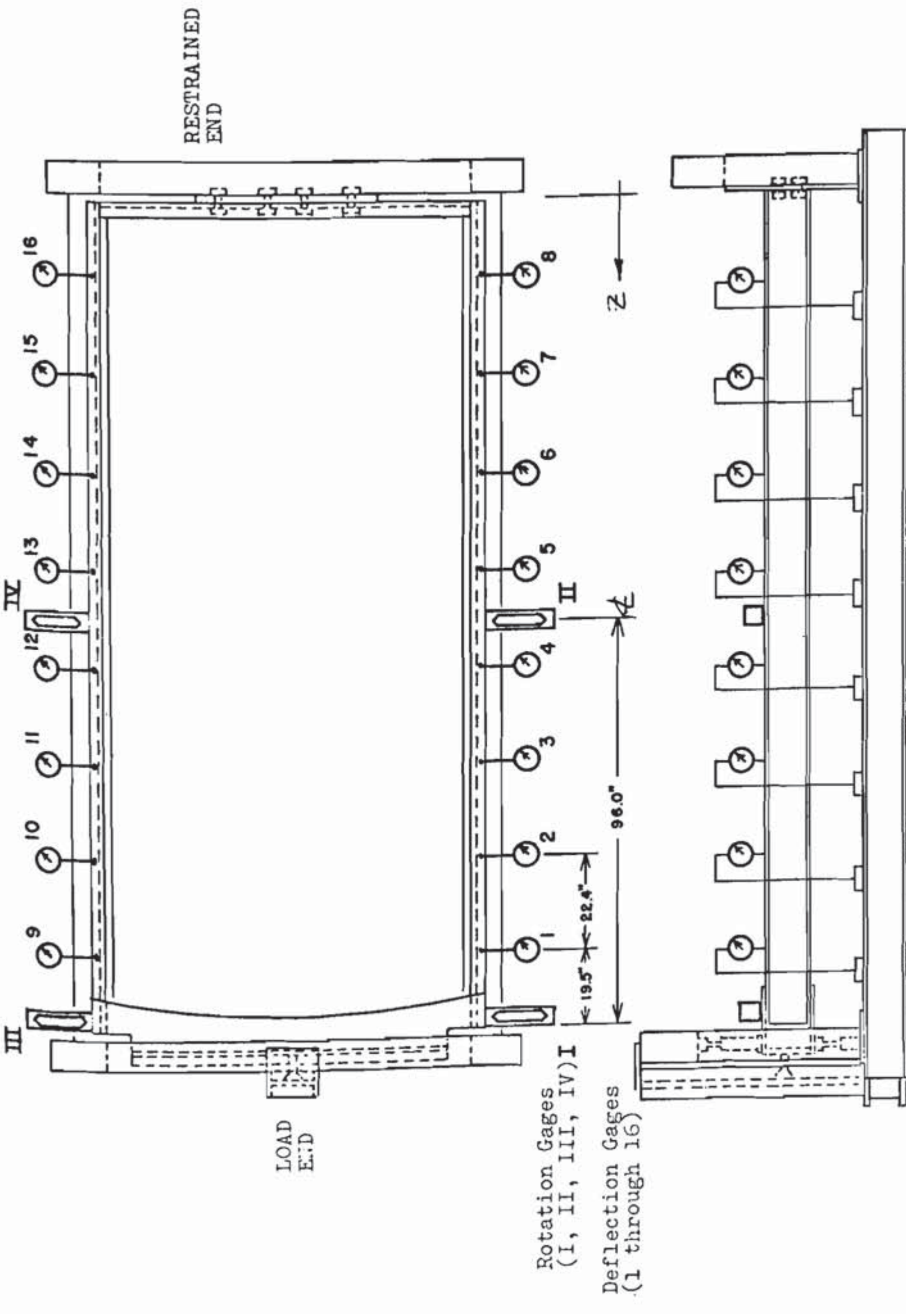

WARPING STRESS RATIO $\bar{\Psi}$ vs. EQUIVALENT
PLATE THICKNESS t_{em}
L = length of beam (ft)
R = width of beam (inches)
L=50 B=96
L=50 B=80
L=50 B=63
L=100 B=96
L=100 B=80
L=100 B=63
L=150 B=96
L=150 B=80
L=150 B=67
Warping Stresses Ratio $\bar{\Psi}$
Equivalent Thickness t_{em} x 10^{-4} (inches)

Figure No. 7



Deflection and Rotation Gage Locations

Figure No. 8

BOX BEAM TEST SPECIMENS

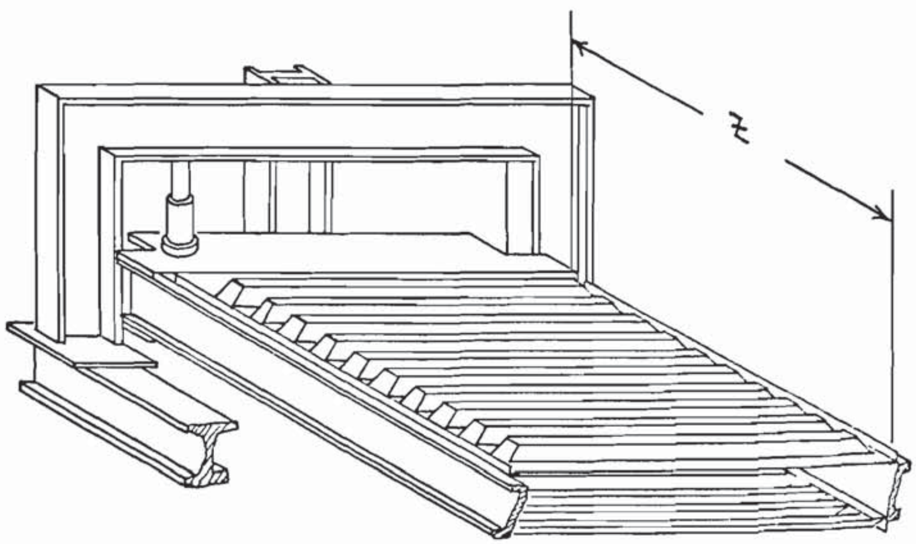


Figure No. 9

Box Beam B-4

Torque T vs. Rotation
at Sections Z/L

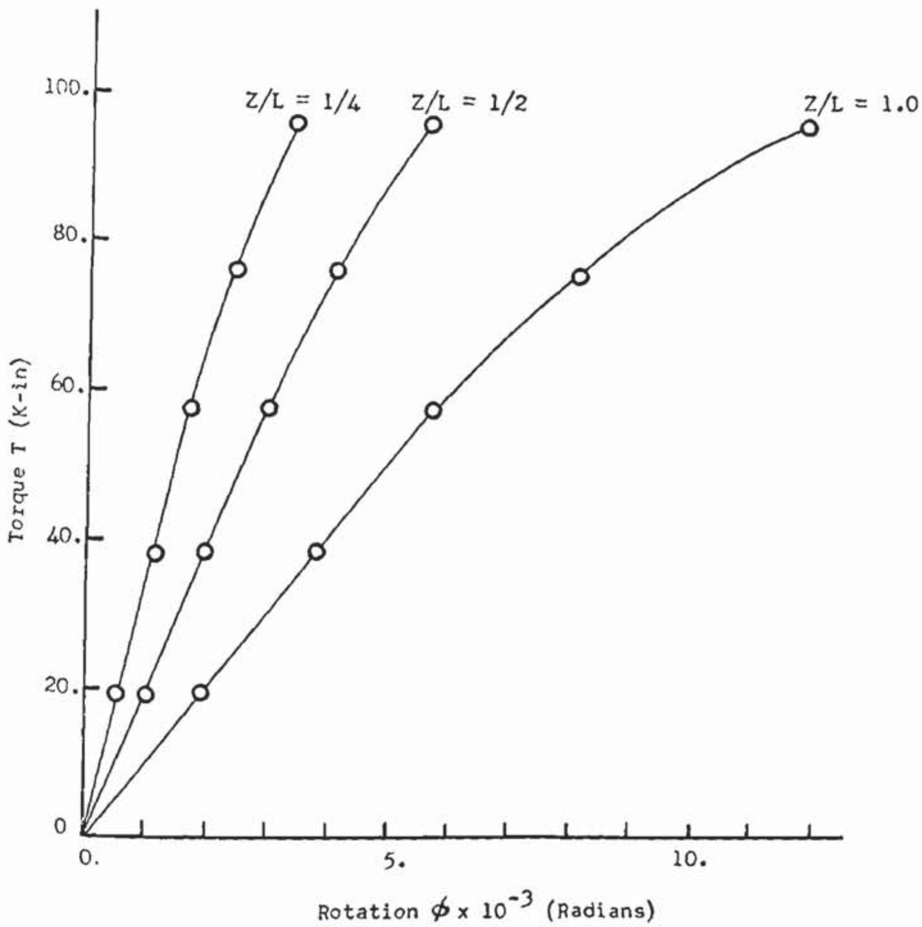


Figure No. 10

Box Beam B-4
Torque T vs. ϕ'

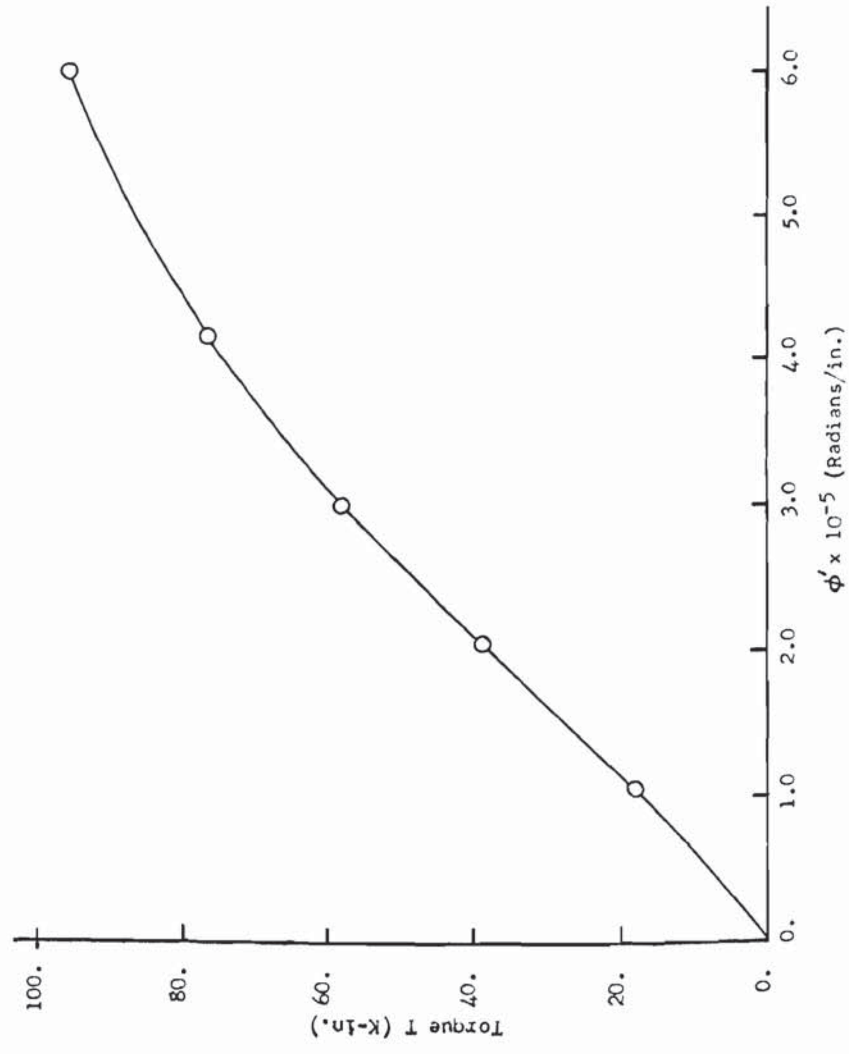


Figure No. 11

TABLE No. 1 EQUIVALENT THICKNESS TE

SPAN (FT) (2L)	5" - PITCH							5½" - PITCH						
	GAGE							GAGE						
	22	21	20	19	18	17	16	22	21	20	19	18	17	16
5	.0066	.0080	.0096	.0127	.0167	.0207	.0249	.0054	.0067	.0080	.0107	.0143	.0180	.0219
6	.0077	.0094	.0112	.0147	.0191	.0234	.0278	.0064	.0078	.0094	.0125	.0166	.0207	.0249
7	.0089	.0108	.0128	.0165	.0212	.0256	.0301	.0074	.0090	.0108	.0142	.0187	.0231	.0276
8	.0101	.0121	.0142	.0181	.0229	.0274	.0319	.0084	.0102	.0122	.0159	.0207	.0252	.0298
9	.0112	.0133	.0154	.0194	.0243	.0288	.0333	.0094	.0114	.0135	.0174	.0223	.0269	.0316
10	.0121	.0143	.0165	.0206	.0255	.0300	.0344	.0104	.0125	.0147	.0187	.0237	.0284	.0330
11	.0130	.0152	.0175	.0215	.0264	.0309	.0353	.0114	.0135	.0158	.0199	.0249	.0296	.0342
12	.0137	.0160	.0182	.0223	.0272	.0316	.0360	.0122	.0144	.0167	.0209	.0259	.0306	.0352

SECTION DIMENSIONS	BB	BT	D	C	BB	BT	D	BS
	.7700	.7710	1.96	.959	.8950	.8960	1.96	1.091

TABLE No. : EQUIVALENT THICKNESS TE

SPAN (FT.) (2L)	6"-PITCH							6 ½" -PITCH						
	GAGE							GAGE						
	22	21	20	19	18	17	16	22	21	20	19	18	17	16
5	.0046	.0057	.0068	.0092	.0124	.0157	.0193	.0039	.0049	.0059	.0080	.0109	.0139	.0172
6	.0054	.0066	.0080	.0107	.0144	.0182	.0222	.0046	.0057	.0069	.0093	.0127	.0161	.0199
7	.0062	.0076	.0092	.0123	.0165	.0206	.0250	.0053	.0066	.0080	.0107	.0145	.0184	.0225
8	.0071	.0087	.0105	.0139	.0184	.0229	.0274	.0061	.0075	.0091	.0122	.0164	.0206	.0250
9	.0080	.0098	.0117	.0154	.0202	.0248	.0295	.0069	.0085	.0102	.0136	.0182	.0227	.0273
10	.0089	.0109	.0129	.0169	.0218	.0265	.0313	.0077	.0095	.0114	.0151	.0198	.0245	.0293
11	.0098	.0119	.0141	.0181	.0232	.0279	.0327	.0085	.0104	.0125	.0164	.0213	.0261	.0309
12	.0107	.0129	.0151	.0193	.0244	.0292	.0339	.0094	.0114	.0135	.0176	.0227	.0275	.0324

SECTION DIMENSIONS	BB	BT	D	C	BB	BT	D	BS
	1.02	1.021	1.96	.959	1.45	1.46	1.96	1.091

TABLE No. 1 EQUIVALENT THICKNESS TE

SPAN (FT.) (2L)	7"-PITCH							7½"-PITCH						
	GAGE							GAGE						
	22	21	20	19	18	17	16	22	21	20	19	18	17	16
5	.0083	.0100	.0120	.0156	.0204	.0250	.0300	.0069	.0084	.0101	.0133	.0177	.0220	.0266
6	.0095	.0115	.0137	.0177	.0230	.0280	.0332	.0080	.0097	.0116	.0153	.0201	.0249	.0299
7	.0108	.0130	.0154	.0198	.0253	.0306	.0358	.0091	.0111	.0132	.0172	.0225	.0276	.0328
8	.0121	.0145	.0170	.0216	.0273	.0326	.0379	.0103	.0124	.0147	.0191	.0246	.0299	.0353
9	.0134	.0159	.0185	.0232	.0289	.0342	.0395	.0114	.0138	.0162	.0208	.0265	.0319	.0373
10	.0145	.0171	.0197	.0245	.0303	.0356	.0408	.0125	.0150	.0175	.0223	.0281	.0335	.0389
11	.0155	.0181	.0208	.0256	.0313	.0366	.0418	.0136	.0161	.0188	.0236	.0294	.0348	.0402
12	.0164	.0190	.0217	.0265	.0322	.0375	.0426	.0145	.0172	.0198	.0247	.0305	.0359	.0413
SECTION DIMENSIONS	BB		BT		D		C	BB		BT		D		BS
	.916		.916		1.96		1.668	1.041		1.041		1.96		1.287

TABLE No. 1 EQUIVALENT THICKNESS TE

<table>
<tr><th rowspan="3">SPAN(FT.)
(2L)</th><th colspan="7">8"-PITCH</th><th colspan="7">-PITCH</th></tr>
<tr><th colspan="7">GAGE</th><th colspan="7">GAGE</th></tr>
<tr><th>22</th><th>21</th><th>20</th><th>19</th><th>18</th><th>17</th><th>16</th><th>22</th><th>21</th><th>20</th><th>19</th><th>18</th><th>17</th><th>16</th></tr>
<tr><td>5</td><td>.0058</td><td>.0072</td><td>.0086</td><td>.0114</td><td>.0152</td><td>.0191</td><td>.0233</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>.0068</td><td>.0083</td><td>.0100</td><td>.0133</td><td>.0177</td><td>.0221</td><td>.0268</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>7</td><td>.0077</td><td>.0095</td><td>.0113</td><td>.0150</td><td>.0199</td><td>.0247</td><td>.0298</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>.0087</td><td>.0107</td><td>.0127</td><td>.0168</td><td>.0226</td><td>.0272</td><td>.0324</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>.0098</td><td>.0119</td><td>.0142</td><td>.0185</td><td>.0240</td><td>.0293</td><td>.0347</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>.0108</td><td>.0131</td><td>.0155</td><td>.0200</td><td>.0258</td><td>.0312</td><td>.0366</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>11</td><td>.0118</td><td>.0142</td><td>.0168</td><td>.0215</td><td>.0273</td><td>.0328</td><td>.0382</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>12</td><td>.0128</td><td>.0153</td><td>.0179</td><td>.0227</td><td>.0286</td><td>.0341</td><td>.0396</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="2">SECTION
DIMENSIONS</td><td colspan="2">BB</td><td colspan="2">BT</td><td colspan="2">D</td><td>C</td><td colspan="2">BB</td><td colspan="2">BT</td><td colspan="2">D</td><td>BS</td></tr>
<tr><td colspan="2">1.660</td><td colspan="2">1.660</td><td colspan="2">1.960</td><td>1.668</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td>1.287</td></tr>
</table>

TABLE 2

DIMENSIONS OF THE BOX SECTIONS

Bridge Type	Span (ft)	A	B	C	D	E	TS	T1	T2	T3
2-L 2-G	50	34'-0"	96"	20"	29 "	12"	7"	0.625 "	0.375 "	0.5 "
2-L 3-G		34'-0"	63"	20"	28 "	12"	6"	0.5 "	0.375 "	0.5 "
3-L 3-G		44'-6"	86"	20"	28.75"	12"	7"	0.5625"	0.375 "	0.5 "
3-L 4-G		44'-6"	63"	20"	28 "	12"	6"	0.5 "	0.375 "	0.5 "
4-L 4-G		55'-0"	80"	20"	28.5 "	12"	7"	0.5 "	0.375 "	0.5 "
4-L 5-G		55'-0"	63"	20"	28 "	12"	6"	0.5 "	0.375 "	0.5 "
2-L 2-G	100	34 -0"	96"	49"	58 "	14"	7"	1.0 "	0.50 "	0.75"
2-L 3-G		34'-0"	63"	49"	57 "	12"	6"	0.75 "	0.4375"	0.75"
3-L 3-G		44'-6"	86"	49"	57.75"	13"	7"	1.0 "	0.4375"	0.75"
3-L 4-G		44'-6"	63"	49"	57 "	12"	6"	0.75 "	0.4375"	0.75"
4-L 4-G		55'-0"	80"	49"	57.5 "	12"	7"	1.0 "	0.4375"	0.75"
4-L 5-G		55'-0"	63"	49"	57 "	12"	6"	0.75 "	0.4375"	0.75"
2-L 2-G	150	34'-0"	96"	76"	85 "	14"	7"	1.50 "	0.625 "	1.00"
2-L 3-G		34'-0"	63"	76"	84 "	13"	6"	1.0 "	0.5 "	1.00"
3-L 3-G		44'-6"	86"	76"	84.75"	13"	7"	1.50 "	0.5625"	1.00"
3-L 4-G		44'-6"	63"	76"	84 "	13"	6"	1.0 "	0.5 "	1.00"
4-L 4-G		55'-0"	80"	76"	84.5 "	12"	7"	1.50 "	0.5625"	1.00"
4-L 5-G		55'-0"	63"	76"	84 "	13"	6"	1.0 "	0.5 "	1.00"

TABLE 3

Diaphragm Test Variables

Test Specimen	Pitch (inches)	Gage	Length 2L (inches)	Width a (inches)	Depth d (inches)	N_r	N_s	Mfg. Co.
D1	6.5	18	84	25	2	5	1	B.S.
D2	5.0	17	84	24	2	5	1	W.C.
D3	6.0	22	58	29	2	5	1	R.B.
D4	8.0	17	84	30	2	5	1	W.C.
D5	6.0	22	73	29	2	5	1	R.B.
D6	6.5	18	84	38	2.5	5	2	B.S.

TABLE 4

Diaphragm Results

Test Specimen	F (Kips)	Defl. (inches)	Equiv. Pl. Thickness		Exp/ Theory
			Theory	Experiment	
D1	1.0	.0140	.001906	.001840	0.96
D2	2.0	.0310	.002192	.001595	0.73
D3	2.0	.0800	.001229	.001083	0.88
D4	2.0	.0450	.001958	.001373	0.70
D5	1.0	.001203	.001203	.000982	0.82
*D6	0.5	.0230	.001635	.000851	0.52

*Buckling of Panel

TABLE 5

Box Beam Test Specimens

Test Specimen	Pitch (inches)	Gage	Length 2L (inches)	Width a (inches)	Depth (inches)	N_s	N_{sh}	t_e	t_{em}	Mfg. Co.
B1	6.5	18	84	117	2.5	5	6	.0062	.00234	B.S.
B2	5.0	17	84	150	2.0	5	6	.0288	.00448	W.C.
B3	8.0	17	84	162	2.0	5	5	.0068	.00320	W.C.
B4	8.0	17	84	162	2.0	40	5	.0068	.00470	W.C.

TABLE 6

Box Beam Torsional Stiffness GK_T

Specimen	$GK_T \times 10^6$ - Theory		$G_{KT} \times 10^6$ - Exper.
	Plate Thickness t_e Criteria	Plate Thickness t_{em} Criteria	
B1	1.734	0.654	.519
B2	8.054	1.258	1.195
B3	1.902	0.895	1.425
B4	1.902	1.314	1.711

t_e - no slip - Equation (6) t_{em} - slip - Equation (10)

TABLE 7

Summary of Normal Stress
Example Analysis

Location	Cross Section Location	Bending σ_b	Torsion σ_w(ksi)		Total σ_t(ksi)	
			Open	Closed	Open	Closed
Mid span	Top Flange Point 2	20.0	10.2	3.6	30.2	23.6